Volume 18 DECEMBER, 1948 Number 3

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 18, NO. 3, PP. 91–99
PLATES 1–3, FIG. 1, DECEMBER, 1948

AUTHIGENIC HEULANDITE IN SANDSTONE, SANTA CRUZ COUNTY, CALIFORNIA

CHARLES M. GILBERT AND MARTIN G. McANDREWS
University of California, Berkeley, California

ABSTRACT

A variety of heulandite occurs as minute idiomorphic crystals and as crusts attached to detrital sand grains in friable marine sandstones of upper Miocene age in southern Santa Cruz County, California. It is certainly authigenic and is typical, in small amounts, of a thin stratigraphic horizon at the base of sandstones containing volcanic detritus.

The mineral has been identified by optical and crystallographic properties determined with a universal stage, and although these properties do not agree exactly with those of either ordinary heulandite or the silica-rich variety, they indicate that the mineral is a type of heulandite.

GEOLOGIC SETTING

Zeolite, considered to be a variety of heulandite, occurs as an authigenic constituent in sandstones in the vicinity of Scott Valley, southern Santa Cruz County, California. This is a region underlain by flat-lying, friable, marine sandstones of upper Miocene age resting on the eroded surface of pre-Cretaceous granodiorite. The portion of the area lying within the borders of the Santa Cruz quadrangle has been mapped by Branner, Newsom, and Arnold (1909) who designated the sandstones overlying the granodiorite as part of the Santa Margarita formation. Eastward from Scott Valley (in the New Almaden or Los Gatos quadrangle), the typically white, massive Santa Margarita sandstone is overlain conformably by bluish volcanic sands similar to those found in the upper Miocene San Pablo group of the central California Coast Ranges. The total measurable thickness of these sandstones, undeformed as they are, is limited by the maximum relief of the country and is at least 600 feet. How much thicker the original accumulation may have been is a matter of conjecture. Furthermore, the Miocene strata in this area may have been buried under as much as 2000 feet of Pliocene sediments, since stripped away by erosion.

The heulandite was discovered during the course of an investigation into the general petrography of the upper Miocene sandstones in this area (McAndrews, 1948). It is a characteristic minor constituent in a thin stratigraphic horizon outcropping in the drainage basin of Branciforte Creek from its headwaters downstream for at least five miles, a horizon which lies on top of the white, nonvolcanic Santa Margarita sandstones and beneath the blue volcanic sands. Heulandite-bearing strata generally contain fragments of volcanic glass (refractive index $1.500 \pm .003$), but characteristically they are arkose composed of detritus from plutonic and metamorphic rocks and are distinct from the blue sands above which are dominantly basaltic and andesitic detritus. The typical mineral composition of these sandstones is indicated in Table 1.

Heulandite-bearing sandstones are brownish and typically more argillaceous than those above and below. Some are medium or fine grained sand mixed with abundant silt and clay; others are coarse pebbly sand or conglomerate with a

minor admixture of fine detritus. The sample (S1–8) containing more heulandite than any other collected was from one of these conglomeratic strata. Throughout, the sandstone is incoherent; indeed, it is so friable that coherent pieces large enough for impregnation prior to thin sectioning are difficult to collect and must be transported with care to prevent crumbling.

crystals or clusters of crystals scattered through the open pores and fine matrix of the sand and also attached to the surfaces of detrital sand grains. Some detrital grains are fringed with heulandite crusts in which most of the crystals tend to be oriented with their maximum dimensions (the plane of the side pinacoid {010}) approximately normal to the surface of the detrital grain. Heulandite

TABLE 1. *Mineral composition of upper Miocene sandstones*[1]

	Tsm[2]	Heulandite-bearing strata							Blue sands[3]
		4	8	14	19	34	39	40	
Quartz	VA	A	VA	A	A	VA	VA	A	C
Plagioclase	VA	VA	VA	VA	VA	A	A	VA	VA
Orthoclase	A	C	A	C	C	C	C	C	R
Rock fragments	A	VA	C	A	VA	VA	VA	VA	VA
Glass		R	R	VA	C		C		C
Heavy minerals	T	R	R	R	R	R	A	C	A
Magnetite	T	T	T		T	R	T	T	A
Other opaques	VA	A	VA	A	A	A	A	A	A
Pyroxenes					R				VA
Basaltic hornblende			T	T	T				A
Hornblende	T	VA	VA	VA	VA	VA	VA	VA	A
Tremolite-actinolite	T	VA	A	A	A	A	A	A	R
Zircon	A	C	A	A	C	A	R	R	R
Garnet	A	C	R	C	C	C	R	R	T
Sphene	A	C	C	C	A	R	T		T
Tourmaline	C	R	T	R	T	R	T		T
Epidote	R	T	T	T	C	T			T
Andalusite	T		T	T	T		T	T	

[1] Letters indicating relative abundance have the following meaning: VA—more than 25%, A—11–25%, C—4–10%, R—1–3%, T—less than 1%. Very rare constituents and those occurring sporadically are not listed but include: glaucophane, clinozoisite, rutile, anatase, brookite, monaxite, xenotime, staurolite, and kyanite.

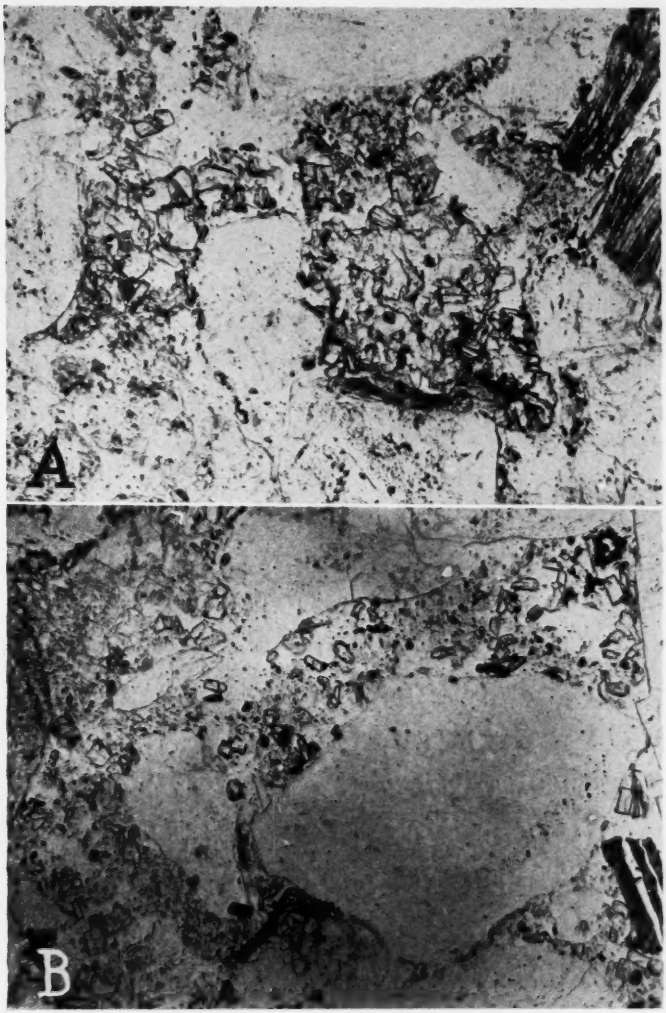
[2] Average of 10 typical Santa Margarita sandstones.

[3] Average of 20 typical blue sands.

MODE OF OCCURRENCE OF THE HEULANDITE

Heulandite is a minor constituent in all of the sandstones that contain it and in the samples collected it forms less than 1 per cent of the rock. Its occurrence in the sandstone is illustrated in Plates 1 and 2 by photomicrographs of thin sections cut from specimens impregnated with plastic.[1] It is found as idiomorphic crystals and crusts are very commonly seen on quartz and feldspar grains, and less frequently they are attached to biotite or volcanic glass. In one instance, heulandite forms a local cement completely filling the spaces between a group

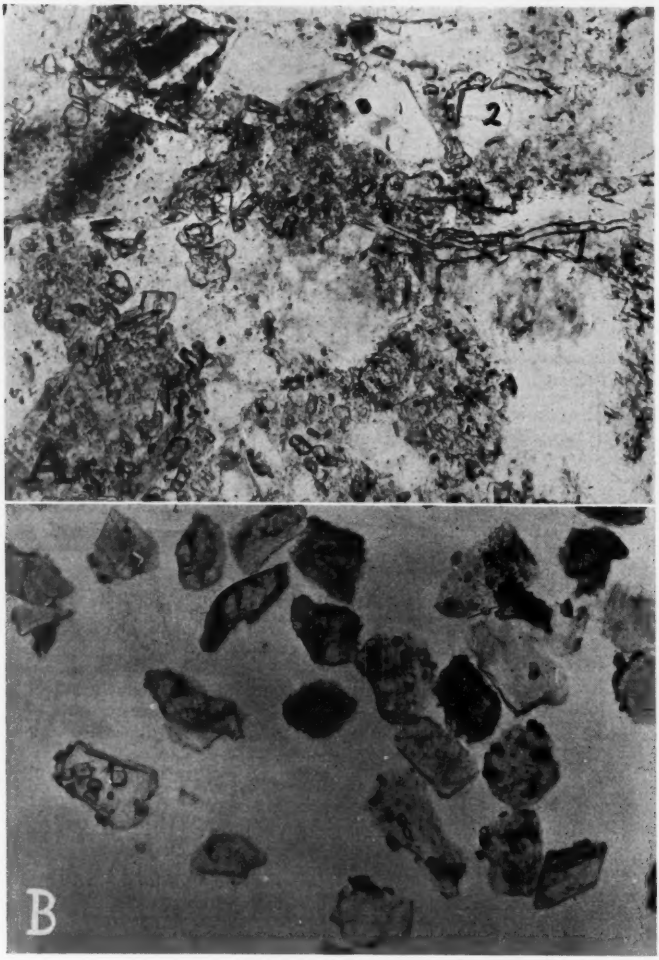
[1] Impregnation was accomplished in a vacuum with Castolite, a thermo-setting plastic which hardens slowly at room temperature and more rapidly in direct sunlight in the presence of a catalyst. The refractive index of hardened Castolite is slightly less than 1.56.



EXPLANATION FOR PLATE 1

PLATE 1. A. Photomicrograph of thin section (S1-8) showing clusters of heulandite crystals largely filling pores between sand grains of quartz, feldspar and biotite (upper right). Magnification 130×.

B. Photomicrograph of thin section (S1-8) showing heulandite crystals scattered through the pores and fine matrix between quartz, feldspar, and biotite (lower right) sand grains. Magnification 110×.



EXPLANATION FOR PLATE 2

PLATE 2. A. Photomicrograph of thin section (S1–8) showing heulandite crystals scattered through the fine matrix between quartz and feldspar sand grains (lower left half of plate) and in the upper right corner a veinlet of heulandite cutting a plagioclase grain (1) and a crust of heulandite crystals partly surrounding a quartz grain (2). Magnification 110×.

B. Photomicrograph of quartz and feldspar grains with minute heulandite crystals attached (sample S1–44). Magnification 130×.

of detrital grains. A few minute heulandite veinlets cut both quartz and feldspar, apparently filling fractures in the sand grains, but no evidence of replacement of any detrital mineral by heulandite has been seen.

Although fragments of volcanic glass (refractive index = 1.500 ± .003) occur in most of the specimens containing heulandite, no particular relationship or association between the two constituents has been observed. Many of the glass fragments appear unaltered, although some cloudy aggregates may be altered glass; and heulandite is no more commonly attached to glass shards than to other detrital grains.

MODE OF ORIGIN

All that can be reported as a result of the present examination is that the heulandite is undoubtedly an authigenic mineral in the sandstones that contain it. Certainly its form and occurrence indicate that it is not detrital, and there is no reason to suspect that it was produced by hydrothermal processes connected with igneous emanations, for the effects of such hydrothermal alteration are not evident in any of the Tertiary sediments in the area. Its characteristic presence in a single thin horizon of loose sandstone, covering at least 10 square miles, and its mode of occurrence in the rock also seem to preclude a hydrothermal origin. Nor has the present study revealed any evidence that the heulandite has been derived by alteration from any particular one of the original constituents in the rock. Bramlette and Posnjak (1933) have described a somewhat similar zeolite[1] in the Miocene Monterey group of California as an alteration product of volcanic ash; but in the present case such an origin cannot be established. To be sure, the sandstones containing heulandite in Santa Cruz County do commonly contain fragments of volcanic glass having a low refractive index, and also the horizon in which it is a characteristic constituent lies immediately beneath sands composed of basaltic and andesitic detritus. Thus heulandite can be said to be associated with the products of vulcanism in this area as in others; but here a genetic connection between them has not been proved.

Regardless of the processes that led to its crystallization in the sandstones, it is certain that heulandite crystallized after deposition of the sands and at low temperatures; and if it was actually derived by alteration of some original constituents of the sand it has migrated at least a short distance through the deposit.

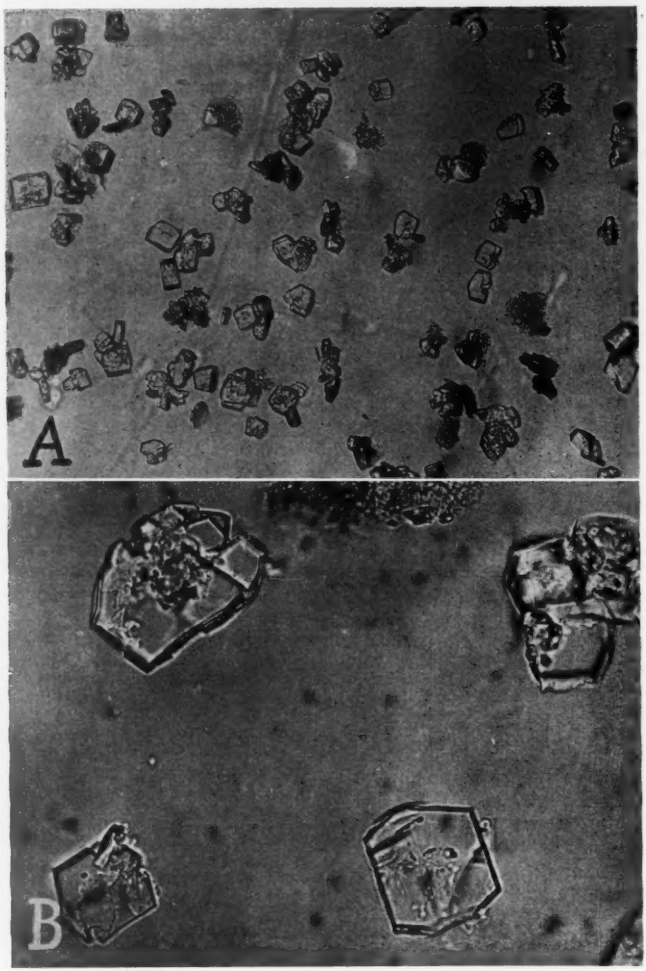
PROPERTIES OF THE HEULANDITE

Behavior in acid.—All of the samples containing heulandite have been cleaned by boiling briefly in 20 per cent hydrochloric acid with no noticeable effect on the mineral.

Specific gravity.—For convenient study under the microscope heulandite concentrates have been prepared by a combination of screening and centrifuging the fine grained fraction (less than 75 microns) in bromoform diluted with alcohol. Heulandite floats in a liquid having a specific gravity of 2.17 and sinks in one having specific gravity 2.06. Using this procedure, concentrates 75 per cent pure may be readily obtained and none more than about 90 per cent pure could be produced.

Crystallography.—Heulandite concentrates contain many perfectly idiomorphic crystals averaging 25 to 60 microns in maximum dimensions (Plate 3). These were mounted in Castolite plastic and placed on a universal stage so that the habit, faces, and interfacial angles could be determined by the method described elsewhere (Gilbert and Turner, 1948, Example 1). Results obtained from measurement of many crystals indicate that the symmetry is monoclinic and the habit tabular parallel to the side pinacoid {010}. Some crystals are thin tablets and others are more nearly equidimensional;

[1] "Clinoptilolite" which has since been classed as high-silica heulandite, as discussed later.



EXPLANATION FOR PLATE 3

PLATE 3. A. Photomicrograph of heulandite concentrate prepared from sample S1–8. Magnification 110×.

B. Photomicrograph of heulandite crystals from concentrate pictured in A. Magnification 450×.

and five crystal forms are typically developed, namely {001}, {201}, {$\bar{2}$01}, {110}, and {010}, as illustrated in Figure 1. Interfacial angles determined on the most perfect crystals with all faces well developed agree within 2 degrees with

those given for heulandite by Dana (1899, p. 574); the discrepancy between the measured and published angles is attributed to error inherent in the method used. The habit agrees perfectly with that of heulandite.

Table 2 gives results obtained from measurement of four crystals together with the interfacial angles for heulandite as given by Dana. The reliability of the results obtained varies with different crystals because precision of measurement is dependent on the accuracy with which the position of each face can be estimated visually. Obviously those crystals with large perfect faces are most suitable, The measurements given in Table 2 are considered to be the most reliable of the many measurements made.

Optical properties.—The birefringence of the authigenic heulandite is very low approximately .007, and the mean refractive index (β) is $1.480 \pm .003$. Other properties determined with a universal stage on heulandite mounted in unheated plastic are as follows; the optic axial angle (2V) varies between 75 and 80 degrees; acute bisectrix (Z) is normal to the side pinacoid {010} and coincides with crystallographic axis *b*; Y is inclined 10–12 degrees to the normal to the basal plane {001} and 8–10 degrees to the *c* crystallographic axis; X is inclined 10–12 degrees to the *a* crystallographic axis.

These optical data do not agree exactly with data given by Dana for heulandite,

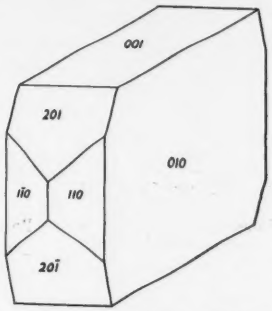


FIG. 1. Habit of authigenic leudandite.

particularly the refractive index which is low in the Santa Cruz zeolite (1.480 as compared with 1.500); they agree more closely with optical data for silica-rich heulandite as given by Hey and Bannister (1943).

Changes on heating.—In minerals of very low birefringence, such as zeolites, slight changes in relative refractive in-

TABLE 2. *Crystal angles of heulandite to nearest degree*

	Heulandite (Dana)	Authigenic heulandite			
		1	2	3	4
(001)∧(201)	64	63	64	63	63
(001)∧(20$\bar{1}$)	114	114	113	114	112
(001)∧(110) (001)∧(1$\bar{1}$0)	89	88, 89	88, 87	88, 89	88
(110)∧(1$\bar{1}$0)	44	45	45	43	45
(201)∧(20$\bar{1}$)	50	50	49	51	49
(201)∧(110) (201)∧(1$\bar{1}$0)	33	32, 34	32	32, 34	32, 34
(20$\bar{1}$)∧(110) (20$\bar{1}$)∧(1$\bar{1}$0)	33	32, 35	32, 35	31, 32	31, 34
Angle β	88½	88	86½	88	88

dices, such as may be caused by heating, produce large differences in such optical properties as orientation and optic axial angle and may even cause a reversal of the optic sign. Large variations in the optical properties of heulandite, produced by heating, are noted by Dana (1899, p. 575). That such changes in optical properties may be produced in zeolite by the heating necessary to harden canada balsam when making thin sections or permanent grain mounts has been noted in the case of thompsonite by C. O. Hutton, in an appendix to a paper by Benson (1942, p. 181). During the preparation of balsam mounts, Hutton found that the elongation of thompsonite was changed from negative to positive. In the present case, when mounted in canada balsam as compared with mounts made in unheated Castolite plastic or immersion oils, the authigenic heulandite undergoes a change in orientation whereby the positions of X and Z are interchanged and the optic sign is reversed from positive to negative. To test whether ordinary heulandite behaves in the same manner, several mounts of heulandite from Cape Blomidon, Nova Scotia and from West Paterson, New Jersey were prepared both in unheated plastic and in canada balsam. These were examined and the resulting changes in optical properties are shown in Table 3.

TABLE 3. *Changes in optical properties caused by heating in canada balsam*

	Optic sign	Optic axial angle (2V)	Orientation
Heulandite from Cape Blomidon, Nova Scotia			
Unheated	Positive	30–35	Z ⊥ (010)
Balsam mount #1	Positive	75–90	Z ⊥ (010)
Balsam mount #2	Positive	72–85	Z ⊥ (010)
Heulandite from West Paterson, New Jersey			
Unheated	Positive	43–45	Z ⊥ (010)
Balsam mount #1	Positive	45–48	Z ⊥ (010)
Balsam mount #2	Positive	70–80	Z ⊥ (010)
Balsam mount #3	Positive	50–60	Z ⊥ (010)
Authigenic heulandite, Santa Cruz Co., Calif.			
Unheated	Positive	75–80	Z ⊥ (010) Y near *c* axis
Balsam mount #1	Negative	75–85	X ⊥ (010) Y near *c* axis
Balsam mount #2	Negative	75–80	X ⊥ (010) Y near *c* axis
Balsam mount #3	Negative	75–85	X ⊥ (010) Y near *c* axis

Although there was no precise control of the temperature and duration of heating during the preparation of the canada balsam mounts,[1] the results clearly indicate that there is a difference in the type, as well as degree, of change in the Santa Cruz zeolite as compared

[1] Presumably the varied results obtained with the New Jersey heulandite were caused by variations in the temperature and duration of preparation of the mounts.

with the others, a fact suggesting that this mineral, although probably heulandite, is not the ordinary variety represented by the other two specimens.

Identification.—It would, of course, be desirable to supplement the data already recorded with a chemical analysis of the authigenic zeolite, and great effort was made to purify the mineral sufficiently for precise chemical analysis, but without success. Concentrates approximately 85–90 per cent pure have been prepared but are not considered satisfactory for the purpose.

Because its crystal habit and interfacial angles are those of heulandite, the mineral discussed has been identified with that species. On the other hand, both its optical properties and its behavior on heating suggest that it is not typical heulandite as described by Dana (1899). Another zeolite having a crystal habit generally similar to that of heulandite but optical properties more like those of the Santa Cruz mineral has been described as mordenite by Pirsson (1890), and accepted as such by Dana (1899). This mineral, although generally similar to heulandite in habit, has a significantly larger interfacial angle between the prism faces present on the crystals, 53 degrees as compared with 44 degrees. Later, Pirsson's mordenite was reconsidered and given the name "clinoptilolite" by Schaller (1932). What is probably the same mineral, also called "clinoptilolite," has been described from bentonites at Dome, Arizona and from partly altered volcanic ash in the Monterey formation of California by Bramlette and Posnjak (1933). Since the publication of these papers, Hey and Bannister (1934) have re-examined Pirson's original material ("mordenite") together with the data given for "clinoptilolite" by Bramlette and Posnjak, and they conclude mainly from x-ray studies that "the minerals examined by Pirsson and by Bramlette and Posnjak are essentially high-silica heulandite, without any simple relation to mordenite or ptilolite" and that "the name 'clinoptilolite' is unsuitable."

The optical properties and habit of the Santa Cruz zeolite appear to be generally similar to those of silica-rich heulandite (=clinoptilolite=mordenite of Pirsson); but the angle measured by Pirsson (1890) between the prism faces on his "mordenite" is significantly larger than the corresponding angle in the Santa Cruz heulandite. This difference seems significant and may be interpreted to mean either that the two minerals have different composition or, less likely, that they are the same but have different prism forms developed in the two cases. In the absence of a chemical analysis of the present mineral, the writers can only indicate thus its close similarity with heulandite and suggest that it represents a compositional variety of that mineral.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 18, NO. 3, PP. 100–107
FIG. 1, DECEMBER, 1948

SEDIMENTS AT THE SOUTHERN TERMINATION OF THE SANGRE DE CRISTO ANTICLINORIUM

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Texas Technological College, Lubbock, Texas

ABSTRACT

Sediments at the southern termination of the Sangre de Dristo anticlinorium range in age from early Pennsylvanian through Dakota (Cretaceous). The study of the materials involved four objectives: 1. The deposits are classified and described as representing basin or platform environments of deposition. 2. The characteristics of the minerals including texture, degree of abrasional wear, heavy mineral suite, inclusions, optical and physical properties are summarized. 3. Tectonics are suggested by the type of deposits and sediments. 4. Recent studies reveal that rocks in the Sangre de Cristo Mountains have been an important source material for sediments since late Pennsylvanian time.

INTRODUCTION

The southern Sanger de Cristo Mountains, a broad anticlinorium, embraces most of the area between the cities of Sante Fe and Las Vegas, New Mexico. The sediments at the southern termination of the anticlinorium attain a thickness of about 4,000 feet and range in age from early Pennsylvanian through Dakota, Cretaceous. Subsequent to deposition of Pennsylvanian sediments tectonics initiated the Sangre de Cristo Mountains and incorporated Pennsylvanian rocks into the anticlinorium. Post-Pennsylvanian sediments, marginal to the uplift, were eroded down dip and crop out in monadnocks and north and west facing escarpments.

FIG. 1. Map showing the general location of the sediments.

Field work in addition to collecting samples involved a study of the deposits for thickness, type of materials, stratification and breaks in sedimentation. Collected samples from two widely separated areas represent as nearly as possible a cross section of the deposits. About 50 grams of materials from each sample were analyzed for characteristics as texture, amount of carbonates, degree of abrasional wear, heavy mineral suite, and optical and physical properties. Data in tables 2, 3, and 4 showing texture, abrasional wear and heavy minerals, represent the average for the deposit.

ENVIRONMENTS OF DEPOSITION

Criteria as outlined by Dapples, Krumbein and Sloss were utilized to determine the environments of deposition and type of deposits for the sediments in southern Sangre de Cristo region.

Cretaceous—*Dakota*—Platform environment, quartz-iron oxide type of sandstone with many characteristics of pure

quartz type.—*Morrison*—Platform environment associated with unstable source area.

Jurassic—*Wingate*—Platform environment, quartz-iron oxide type of sandstone.—*Chinle*—Platform environment associated with unstable source area.

Triassic—*Santa Rosa*—Platform environment, quartz-muscovite type of sandstone.—*Siltstone and limestone*—Marginal position in platform environment.

Permian—*Glorietta*—Platform environment, pure quartz type of sandstone.—*Sangre de Cristo*—Basin environment, arkoses, sandstones and shales.

Pennsylvanian—*Magdalena*—Geosynclincal environment with many characteristics of platform limestones.

Pennsylvanian sediments probably represent a geosynclinal environment of deposition, but the Madera limestones reveal characteristics of platform deposits. The sediments attain a thickness of about 2,000 feet and in ascending order are: dark gray crystalline limestones, local lenses of coal; gray, medium grained sandstones; dark gray indurated shales; massive limestones and cherts; and arkosic limestones. Deposition in early Pennsylvanian time, as suggested by the upward gradation from limestones into coal and sandstones, exceeded the rate of subsidence. However, during the deposition of the cherty limestones, middle and late Magdalena time, subsidence probably exceeded the supply of sediments. The limestones are dense, fossiliferous, some are cherty, range from light gray to nearly black and have a wide areal distribution.

During Permian time the environments of deposition in ascending order include: a basin sandstone, a platform sandstone, and a platform limestone. Deposits representing the basin environment filled the structural basins adjoining the southern Sangre de Cristo Mountains. The sediments are fluvial, poorly sorted and consist mainly of unconsolidated mica-

TABLE 1. *Rock classification, after Read and Andrews*

System	Group	Formation	Member
Cretaceous	Colorado	Dakota	
Jurassic		Morrison	
		Wingate	
Triassic	Dockum	Chinle	
		Santa Rosa	
Permian		San Andres	Siltstone
			Limestone
			Glorietta
		Yeso	
		Sangre de Cristo	
Pennsylvanian	Magdalena	Madera	Arkosic limestone
			Cherty limestone
		Sandia	Clastic member
			Lower limestone
Pre-Cambrian			

ceous sands, arkoses and clays. Particles of sand sizes are angular and sub-angular and include an abundance of unstable minerals as hornblende, feldspars and biotite.

Sediments in basin environment of deposition grade into platform sandstones, pure quartz type (Glorietta formation). The sandstones are quartzitic, cross-laminated and in the type section, Glorietta Mesa, attain a thickness of about 130 feet. The deposits are widespread and thicken northward, westward and eastward from the type locality. The quartz grains are well rounded, constitute about 90 per cent of the rock and except in the basal beds are free of iron stain.

The limestones and siltstones of late San Andres time probably occupy a marginal position in the platform environment. The limestones are dark gray, about 20 feet thick, but southward and eastward from the Sangre de Cristo region they are light gray, dolomitic, increase in thickness and reveal most of the characteristics of a platform deposit. The siltstones are red, about 70 feet thick, well sorted and grade laterally into calcareous materials.

Triassic sediments, basal sandstones and upper red shales, were deposited on a broad alluvial plain in the platform environment. The basal sandstones, Santa Rosa formation, quartz-muscovite type, are compact, restricted areally, grade into red shales and attain a thickness of about 80 feet. The sandstones are cross-laminated, moderately well sorted and consist mainly of sands interlensed with clays and conglomerates. The abundant minerals in the light fraction are quartz, muscovite and biotite. The heavy mineral suite contains a wide variety of mineral species of which zircon, tourmaline and magnetite are abundant.

The upper shales, Chinle formation, a deposit on a stable platform associated with an unstable source area, are widespread, uniform in thickness and consist chiefly of red shales and silts interlensed with sands. Abrupt local changes in lithology are numerous. The clays are micaceous, associated with arkosic sands, and some are calcareous.

Deposits during Jurassic time include basal sandstones, medial limestones and evaporites, and upper shales. The sandstones, a platform deposit, quartz-iron oxide type, are compact, moderately widespread, cross-laminated, red to buff, about 100 feet thick and contain thin layers of clays. The sands are cemented with silica, well sorted, about 40 per cent of the grains are rounded and the quartz particles are partly coated with iron oxide.

The shales, a platform deposit associated with unstable source area, are varicolored, green, pink and gray predominating, and contain layers of pink to

TABLE 2. *Average texture in per cent*

	Mesh						
	8	14	28	48	100	200	Clay
Dakota		5.8	22.0	58.2	11.4	1.0	7.8
Morrison		.4	2.8	11.0	27.2	1.8	56.8
Wingate		.9	4.2	40.2	36.6	2.9	17.2
Chinle			.6	8.0	19.2	3.2	69.0
Santa Rosa	.1	1.2	6.3	43.2	27.6	2.9	18.7
Siltstone			1.8	20.2	12.0	5.4	60.6
Glorietta		.3	21.3	65.6	10.1	.8	1.9
Yeso	.2	4.6	16.6	36.6	22.6	9.6	10.0
Sangre de Cristo	.1	2.6	11.9	21.9	10.5	7.0	46.0
Magdalena		1.1	12.6	47.5	22.2	4.6	12.0

gray, consolidated sandstones. The deposits are uniform, about 200 feet thick, widespread, and thin eastward from the Sangre de Cristo region. The limestones and evaporites are probably lacustrine and grade laterally into clays and silts.

Sediments of Dakota age, a platform deposit, quartz-iron oxide sandstone with many characteristics of pure quartz type, are cross-laminated, interlensed with conglomerates and shales and attain a thickness of about 80 feet. The sands are cemented with silica, moderately well sorted and about 50 per cent of the grains are rounded. The heavy mineral suite is characterized by an abundance of magnetite, tourmaline, hornblende and zircon. Some quartz grains are partly coated with iron oxide.

TABLE 3. *Per cent of angular, sub-angular and rounded grains*
R = Rounded, SA = Subangular, A = Angular

	Tourmaline			Zircon			Quartz		
	R	SA	A	R	SA	A	R	SA	A
Dakota	45	45	10	42	44	14	40	44	16
Morrison	39	44	17	40	42	18	38	41	19
Wingate	40	46	14	39	44	17	37	45	18
Chinle	22	48	30	32	48	20	24	50	26
Santa Rosa	27	45	28	32	44	24	22	47	31
Siltstone	23	44	33	26	40	34	27	39	34
Glorietta	34	47	19	38	50	12	31	47	22
Yeso	20	47	33	22	54	24	21	48	31
Sangre de Cristo	17	45	38	20	47	33	20	47	33
Magdalena		60	40		65	35		55	45

CHARACTERISTICS OF THE SEDIMENTS

The sediments for each formation were classified into three groups: coarse grained clastics, sand sizes, arkoses and conglomerates; fine grained clastics, clays and silts; and non-clastics, calcareous materials, cherts and evaporites.

Pennsylvanian sediments, unconformable above pre-Cambrian, in the order of abundance are limestones, sandstones, shales, arkoses and cherts. The coarse grained clastics constitute about 30 per cent of the total deposit. Particles of sand sizes, angular to sub-angular, are concentrated in the upper clastic member of Sandia formation and in sandstone lenses associated with Magdalena limestones. Sands in Pennsylvanian deposits contain an abundance of quartz and muscovite, slightly smaller quantities of hornblende and tourmaline and a few grains of ilmenite, garnet, magnetite, zircon, biotite, anatase, rutile and feldspars. Variation in frequency of the minerals include; horneblende is concentrated in the basal deposits; maximum abundance of garnet, magnetite, zircon and biotite is in the sediments of middle and late Magdalena time; anatase is associated with arkosic limestones; rutile and feldspars are restricted to late Pennsylvanian deposits. Minerals with the exception of hornblende, biotite and feldspars are free of alteration products.

Arkosic materials consisting of large angular fragments of quartz, muscovite and feldspars, chiefly microcline and plagioclase, and associated minerals, hornblende, tourmaline, magnetite and micas, are inclosed in the limestones of late Magdalena time.

The fine grained clastics constitute about 15 per cent of the total deposits and occur as thick beds in the upper clastic member of Sandia formation, lenses in limestones, and insoluble residues in calcareous materials. The clays are gray to black, thinly laminated, partly indu-

rated and some are siliceous. The minerals consist of an abundance of quartz and micas and small quantities of hornblende, magnetite, garnet and tourmaline.

About 55 per cent of Pennsylvanian sediments are nonclastics and consist of calcareous materials and cherts. The limestones are light gray to black, fossiliferous and range in texture from crystalline to dense. Insoluble residues, about 12 per cent of the rock, consist of gray to black clays, chert and a few grains of sand.

Cherts occur as beds of nearly pure silica and insoluble residues in most limestones. The beds of silica, associated with limestones of late and middle Magdalena time, range in thickness from a few inches to a maximum of about 20 feet. Bedding planes extend from the limestones through the chert but the change in materials from calcareous to siliceous is abrupt. The cherts are white to dark gray, contain dark bands and inclose mica flakes, grains of detrital quartz and spicules of sponges. The insoluble residues are gray to chalky and occur as clustered and skeletal masses.

Permian deposits, a series of sediments more than 1,000 feet thick, represent a change of facies from non-marine in basal sediments to marine in middle and late Permian. The high degree of abrasional wear, absence of unstable minerals, polished appearance of the quartz and the heavy mineral suite, suggest that during the deposition of the marine sandstones, middle Permian, the supply of sediments was restricted and the deposits consist largely of reworked materials.

The conditions of deposition, reworking of the clastics, and the volume of materials are largely responsible for the variations in the characteristics of the Permian sediments, especially particles of sand sizes. 1. The abundance of rounded sand grains increase upward from the base, attain a maximum of 34 per cent in Glorietta sandstones, and decrease in siltstones of late San Andres. 2. The occurrence of magnetite decreases from a maximum of 55 per cent of the heavy minerals in early Perian sediments to a maximum of 20 per cent in Glorietta sands and increase late in the period. 3. Magnetite in the non-marine sediments consist of angular reddish-brown particles, partly altered to hematite, but in the marine deposits the grains are rounded, silver gray to black and strongly magnetic. 4. Grains of hornblende are numerous in early Permian time, rarely encountered in Glorietta sands and increase to a high of 20 per cent of the heavy minerals in the siltstones. 5. Muscovite, biotite and feldspars, important constituents of non-marine sediments, are restricted to a few grains in late Permian deposits. Quartz is represented by three varieties, clear, milky and jasper, and most grains in fluvial deposits are iron stained but in

TABLE 4. *Frequency of heavy minerals in per cent. From left to right, magnetite, ilmenite, tourmaline, garnet, epidote, hornblende, zircon, rutile and leucoxene*

	M	I	T	G	E	H	Z	R	L
Dakota	25.6	1.2	29.4	.8	1.2	16.4	24.3	1.1	
Morrison	44.9	3.9	11.6	9.9	6.3	18.1	4.0	.9	.4
Wingate	62.3	4.4	6.4	10.2	6.6	.6	7.1	1.4	1.0
Chinle	31.5	7.7	15.5	9.7	2.7	4.8	19.3	8.2	.6
Santa Rosa	21.3	4.8	18.0	9.0	2.7	8.2	31.3	11.7	2.0
Siltstone	36.0	4.8	9.5	5.3	3.4	20.9	14.9	4.1	1.1
Glorietta	20.9	4.2	24.1	1.4	1.4	.4	26.4	1.7	8.5
Yeso	61.1	6.9	5.4	5.2	.8	.8	15.4	2.9	1.5
Sangre de Cristo	55.5	5.3	7.4	4.6	1.1	11.0	5.6	8.5	1.0
Magdalena	19.6	2.2	27.2	6.4	2.6	32.2	6.2	3.6	

San Andres formation the grains are polished and free of stain. 7. Angularity of sand particles in siltstones increases upward from the base.

The fine grained clastics, about 30 per cent of Permian sediments, are concentrated in the siltstones of the San Andres formation, and in early Permian fluvial deposits. The clays and silts in siltstones are orange to red, about 70 feet thick, moderately well sorted, some are calcareous, as high as 11 per cent, others are siliceous and partly indurated. Clays in fluvial deposits are vari-colored, red orange and green, arenaceous and highly calcareous. The abundant minerals in the clays and silts are quartz, micas and calcite.

The calcareous materials, chiefly impure limestones, are found in the deposits of late Yeso and in the limestone member of San Andres formation. Calcareous sediments in the Yeso formation are light gray, interlensed with sands and some are dolomitic. The materials in the limestone member are dark gray, cavernous and attain a thickness of 20 feet. The insoluble residues, about 10 per cent of the rock, consist largely of sponge-like clays in a skeletal network of fibrous gypsum and a few sub-angular sand particles.

Arkoses, an important constituent of basin deposits of early Permian time, are terrestrial and were probably weathered and transported under semi-arid conditions. The arkosic materials are in lenses and consist of large angular fragments of quartz, muscovite and feldspars in a matrix of sand and clay.

A thick blanket of Triassic sediments, chiefly sandstones and shales, were deposited on a broad fluvial plain. The degree of abrasional wear and the texture of the coarse grained clastics is fairly uniform. The heavy mineral suite in basal sandstones, Santa Rosa formation, is characterized by an abundance of magnetite, tourmaline and zircon, smaller quantities of ilmenite, garnet, hornblende and rutile, and a few grains of epidote and leucoxene. The heavy minerals in sandstone lenses in upper shales as compared to those in Santa Rosa formation reveal dissimilarities in frequency of the mineral species: magnetite increases from 21 to 31 per cent; hornblende, tourmaline, zircon and rutile are less numerous. The minerals with specific gravity less than bromoform include an abundance of quartz, about 50 per cent iron stained, smaller quantities of mica, chiefly muscovite, and a few grains of feldspars.

The fine grained clastics are varicolored, concentrated in the Chinle formation and attain a thickness of about 450 feet. Some clays are calcareous, as high as 20 per cent; others are siliceous, partly indurated and difficult to deflocculate. The red color is a coating of iron oxide which is removed by boiling in dilute hydrochloric acid. The abundant minerals in the clays and silts are quartz, micas, magnetite and zircon.

Triassic sediments in Sangre de Cristo region as compared to those in exposures about 60 miles to the south near the town of Santa Rosa are strikingly similar. However, there are a few minor differences. The decrease in frequency of magnetite and hornblende and a corresponding increase in garnet, chloritic matter and rutile is notable. Feldspars are rarely encountered in sediments at Santa Rosa. Alteration of hornblende, biotite and magnetite is less apparent in the Sangre de Cristo region.

Jurassic deposits in ascending order are basal sandstones, limestones, evaporites and shales. The high degree of abrasional wear on sand particles, about 40 per cent rounded as compared to 18 per cent in underlying Triassic, suggests that the deposits are largely reworked materials. The heavy mineral suite in basal sandstones is characterized by an abundance of magnetite, small quantities of ilmenite, tourmaline, garnet, epidote, zircon, hornblende and leucoxene. The heavy mineral content of the sands in the Morrison formation as compared to that in the basal sandstones include: a decrease in abundance of magnetite from 62 to 45 per cent, and a notable increase in the frequency of hornblende,

tourmaline, biotite, muscovite and feldspars.

Clays and silts are brown to gray, conformable above the evaporites, and constitute about 60 per cent of the materials in the Morrison formation. The calcareous clays of early Morrison time, about 25 feet thick, grade into siliceous clays that are partly indurated, difficult to deflocculate and some contain a skeletal network of gypsum. The mineral content of the clays include an abundance of quartz, gypsum, magnetite and zircon.

Calcareous materials and evaporites are probably lacustrine, attain a thickness of 45 feet and grade into clays and silts. The limestones are dark gray, about four feet thick and the insoluble residues, about 14 per cent of the rock, consists of clays, gypsum and detrital quartz. The evaporites, nearly pure gypsum, are variable in thickness and the chief exposures are in the escarpment five miles southwest of the city of Las Vegas, New Mexico.

Deposits during Dakota time consist of consolidated sandstones interlensed with shales and conglomerates and probably represent a near shore facies of deposition. Particles of sand sizes are characterized by the high degree of abrasional wear (about 40 per cent rounded), the abundance of detrital quartz, and the heavy mineral suite. Most of the quartz grains are platy, coated with iron oxide and inclose an abundance of dust-like particles and gas cavities. The heavy mineral suite is distinguished by the frequency and properties of the minerals: magnetite, tourmaline and zircon are abundant and equally important; hornblende is a common mineral and is represented by light and dark green irregular particles and light green prisms; garnet, rutile and epidote are rarely encountered.

RELATION OF TECTONICS TO SEDIMENTATION

Tectonics during the deposition of the sediments in the southern Sangre de Cristo region influenced the supply and type of materials; the change in facies of deposition; the accumulation of thick deposits of marine sediments; and degree of abrasional wear. The supply and type of materials are related to the uplift of the source areas and the uncovering of source rocks. The change in facies and deposition of thick sections of marine sediments was probably initiated by subsidence of the area receiving deposits. The degree of abrasional wear on the clastics is probably related to the relief of the source area. A low terrane decreases the volume of materials and favors the reworking of exposed sediments.

Three diastrophic movements are recorded in the Pennsylvanian deposits. Orogeny during the deposition of the sediments in Sandia formation, according to Read and Wood, 1947, involved three positive areas: Sierra Grande arch; Uncompahgre axis; and Pedernal axis. The uplift of the source areas was probably responsible for the increase in volume of sediments, the change in texture from basal limestones to sandstones, the local breaks in sedimentation, and the abundance of angular and sub-angular sand particles.

The thick deposits of dark gray massive limestones and associated bedded cherts suggest that during middle Magdalena time subsidence of the geosyncline was equal to or probably exceeded deposition.

Orogeny in late Pennsylvanian time is suggested by deposits of arkosic materials, change in facies of deposition from marine to fluvial, increase in texture and angularity of clastics, and the additional supply of materials, especially garnet, magnetite, biotite, epidote and tourmaline.

Sequence of events in ascending order during deposition of Permian sediments are: deposition of fluvial materials, arkoses, unconsolidated sands and clays; advance of the sea and deposition of about 200 feet of marine sediments; withdrawal of the seas and erosion. Subsidence in early San Andres time was

probably associated with the advance of the seas and deposition of marine sediments. Emergence was probably responsible for the increase in angularity and texture of the clastics and change of facies from marine to non-marine.

Triassic deposits are non-marine, widespread, consist of sandstones and shales, and attain a thickness of about 600 feet. Evidence of major tectonics is not recorded in the sediments, however, source areas which supplied the volume of materials equivalent to Triassic deposits were probably uplifted as denudation progressed.

Subsidence beginning in early Dakota time is suggested by the change of facies from non-marine to marine, thick deposits of Cretaceous sediments, and the unconformable relations of marine sandstones above the Jurassic.

SOURCE AREAS FOR SEDIMENTS

Positive areas that influenced sedimentation in southern Sangre de Cristo region include: uplifts prior to Pennsylvanian time, Sierra Grande arch, Uncompahgre axis, and Pedernal axis; and post-Pennsylvanian uplands of Sangre de Cristo Mountains. A comparison of the weathered materials from pre-Cambrian rocks in the Sangre de Cristo Mountains with the sediments south of the anticlinorium reveal common characteristics. 1. Inclusions in quartz, tourmaline, zircon, garnet, hornblende and micas are strikingly similar. 2. Rectangular and spotting surface markings are characteristics of the garnets. 3. Some zircons are fractured at right angles to long axis, others contain a white central core with radiating cracks and many grains are foliated. 4. Tourmaline from pegmatites are an important constituent of sediments since early Permian time. 5. Arkosic materials, especially feldspars, are similar to those in the granite terrane of the Sangre de Cristo Mountains.

SUMMARY

The sediments south of the Sangre de Cristo anticlinorium are about 4,000 feet thick and represent three marine and two non-marine environments of deposition. Rounded sand grains, a measure of abrasional wear, are absent in Pennsylvanian deposits but attain a maximum of about 40 per cent in Dakota sandstones. Orgeny during the deposition of the sediments is suggested by deposits of arkosic materials, change of facies of deposition, thick deposits of marine sediments, and variation in frequency of minerals, especially, feldspars, biotite and hornblende. Source areas that influenced sedimentation are: pre-Pennsylvanian positive areas, Sierra Grande arch, Uncompahgre axis and Pedernal axis; and the post-Pennsylvanian uplands of the Sangre de Cristo Mountains.

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PLATES I–X, FIGS. 1–2, DECEMBER, 1948

CEMENTATION OF DAKOTA SANDSTONES OF THE COLORADO FRONT RANGE

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ABSTRACT

Field and petrographic studies of sandstones of the Dakota group from the Colorado Front Range show distinct variations in the type and degree of cementation. These variations occur not only vertically in the section but also laterally. The results of investigations of this subject are presented, including discussions of the types, age-relations, and derivation of cementing materials, variations in degree of cementation, and the importance of the "Riecke principle" in the cementation of sandstones.

INTRODUCTION

The Dakota group of the Colorado Front Range consists of a variable group of sandstones and shales which unconformably overlie the variegated shales, thin sandstones, and fresh-water limestones of the late Jurassic Morrison formation and are conformably overlain by the marine shales (Benton, Graneros, etc.) of the Upper Cretaceous sea. Over most of the Front Range the Dakota group is divisible into a lower sandstone, middle shale, and upper sandstone. In southeastern Colorado the lower sandstone and middle shale have been shown to be of Lower Cretaceous (Washita) age. In many localities a middle sandstone is found which is separated from the other sandstones by shale members. The lower shale is more limited in extent than the upper shale.

Field investigations by the writer in the fall of 1946 and the spring and summer of 1947 show that there is considerable variation in the lithification and degree of cementation of the sandstone members of the Dakota group. Locally these sandstones are so strongly cemented that the rock breaks across the grain, i.e., they are true sedimentary quartzites (orthoquartzites), whereas sandstones from other beds at the same locality may be disaggregated by crushing between the fingers. These variations in cementation occur both vertically and laterally in the section.

The importance of the factors controlling cementation to the proper interpretation of the sediments is obvious. Owing to the paucity of literature on this subject a detailed petrographic study was undertaken in an attempt to solve the following problems:

1. Types and age-relations of cementing material in sandstones of the Dakota group.
2. Derivation of cementing materials.
3. Reasons for variation in degree of cementation.
4. Importance of the "Riecke principle" on the cementation of sand grains.

The samples studied are outcrop samples collected along the Front Range from a few miles south of Colorado Springs northward to Soldier Canyon, near Fort Collins.

TYPES AND AGE-RELATIONS OF CEMENTING MATERIALS

Waldschmidt (1941, p. 1839) distinguishes two major types of

> . . . cementing or binding materials: first, those in which the grains are bound together by argillaceous materials; and second, those in which crystalline materials form the cement or bond.

It is admitted that the mechanism by

which clays bind discrete particles may not be cementation "in sensu stricto," but the expression "argillaceous cement" is in common usage. In this paper all cementing or binding materials are considered cements regardless of the method by which the discrete particles are held in place. The terminology used in describing cements is that of Allen (1936).

The chief cementing materials of sandstones of the Dakota group are silica, iron oxides, and clay. Calcarinate cement is minor and is found in only a few samples. These cements are in part primary, in part secondary.

SILICINATE CEMENT

Although there is some secondary silicinate cementation in most, if not all, orthoquartzites, the majority of writers consider that the process is quantitatively unimportant. Krynine (1941, pp. 112–113) states that

> Although the evidence for such secondary silicification is very spectacular, the real importance of this process is very limited on a volumetric basis. Probably close to 95 per cent of the "secondary" silica in the Oriskany (and in many if not most other quartzites and cherts) is really of primary, penecontemporaneous sedimentary origin.

Thin sections of Dakota sandstones cemented by silicinate cement show varying degrees of secondary silicinate cementation. In some sandstones almost every grain is secondarily enlarged. However, the overall average of the secondary silica on the sand grains would not exceed ten per cent of the silicinate cement by volume.

No long period of time seems to be necessary for the development of new crystal faces due to secondary enlargement. Maxwell (1934) conducted experiments in which grains of quartz (lacking in secondary enlargement) were placed under a confining pressure of approximately 8,000 pounds per square inch and at a temperature of 150–200 degrees Centigrade. Water and iron oxide were added and the grains left under heat and pressure for 8 days. At the end of that time the grains were enlarged. A repetition of these experiments with a carbonate solution rather than water and iron oxide did not result in secondary enlargement of the quartz grains.

Waldschmidt (1941), in his comprehensive study of cores from sixteen different sandstone horizons in the Rocky Mountain area finds that a definite sequence in the order of deposition of cementing materials is always observed—where four cementing materials are present, they always precipitate in the following-order:

1. Quartz
2. Dolomite
3. Calcite
4. Anhydrite

ARGILLACEOUS CEMENT

Most of the argillaceous cement in Dakota sandstones is primary, deposited at the time of deposition of the sediment or shortly afterward. A notable exception to this statement is found in the basal Dakota conglomerate at Spring Canyon, near Ft. Collins. Here lenses of clay are associated with a pebbly granule conglomerate (see Plate I). The interstitial relationship of the clay lenses is such as to indicate their deposition at a later date than the pebbles, granules, and very coarse sand grains which make up most of the rock. Dr. W. O. Thompson (1947) has suggested that the clay was deposited by ground water percolating the porous gravel before cementation into its present orthoquartzitic texture. X-ray diffraction patterns show that this clay is a combination of hydromica and kaolinite. However, the binding action exerted by exceptional occurrences of this type is very small, being limited to the peripheral sand grains bordering the lens of clay, and is of little consequence compared to the binding action exerted by clay particles when disseminated throughout a sandstone.

FERRUGINATE CEMENT

Except for Maxwell's (1934) study of the Lyons formation, none of the papers

previously cited found cementation by iron oxides to be important. This lack of mention of ferruginate cement is particularly noticeable in that section of Waldschmidt's paper dealing with sandstone members of the Dakota group. Investigations by the present writer, working entirely with outcrop samples, indicate that ferruginate cement is second in importance only to silicinate cement in Dakota sandstones, and that ferruginate cement is the dominant cement in many samples.

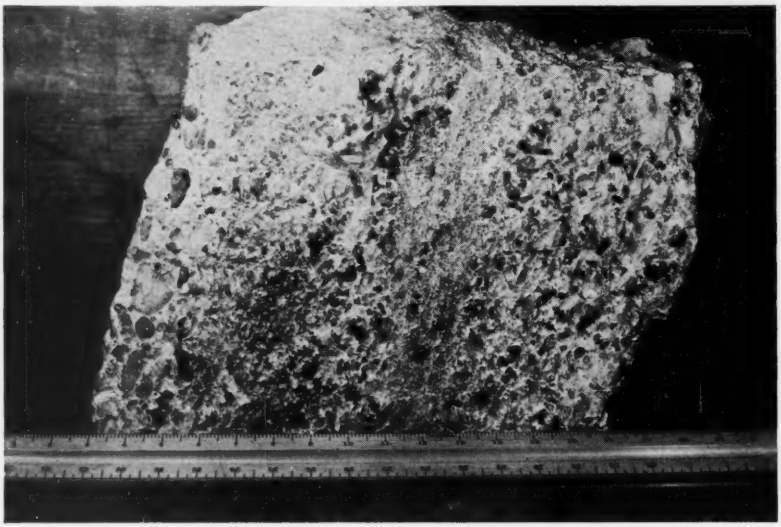

PLATE I. Pebbly granule conglomerate in basal Dakota, Spring Canyon.

Under reflected light, ferruginate cement in Dakota sandstones is commonly light orange in color, consisting of a mixture of hydrated iron oxides with limonite predominating. In a few samples hematite is the dominant cementing material, and the specimen is red-brown in color.

Even under high magnification the discrete particles of ferruginate cement cannot be seen; it is believed that they are well within the clay particle size range. Crushing thoroughly and decanting with water serves to remove much of the coloring matter from a sample.

A very simple experiment may be used to prove that ferruginous materials do act as cements. Chips of ferruginous sandstones are ground to about twice the normal thickness of a thin section (to 0.06 mm.) and a ring of bakelite is built up considerably above the surface of the section. The bakelite must be of such a consistency that it penetrates from the surface to the slide glass, but does not have sufficient fluidity to permeate the portion of the chip either inside or outside the ring. A drop of dilute HCl is placed inside the bakelite ring and the area is leached. Several repetitions of this treatment serve to dissolve all the ferruginous material inside the ring. The leached sandstone crumbles at the slightest touch although the area outside the ring is still hard.

Petrographic studies indicate that ferruginate cement may be either primary or secondary, but secondary cementation is of little volumetric importance. Most ferruginous material is either deposited concurrently with the detrital particles, or is carried in by percolating ground water before induration is complete. Capillary action serves to concentrate the iron-bearing solutions in the finer particles until evaporation, precipitation, and cementation takes place.

Secondary ferruginate cementation may result from the alteration of iron-bearing minerals after induration. In such cases the clogged pores and lack of circulation of fluids between the sand grains hinders redistribution of the products of weathering. Many writers have noted the occurrence of spherical spots of limonite scattered irregularly through some of the Dakota sandstones. These are due to the diagenetic alteration of grains or nodules of pyrite or marcasite. The hydrated iron oxides formed are not widely distributed but remain in a small spherical area around the old nucleus, although all trace of the original pyrite or marcasite may be gone. This is an example of epigenetic ferruginate cementation, as the spherical, radiating spots are commonly more indurated than the surrounding areas.

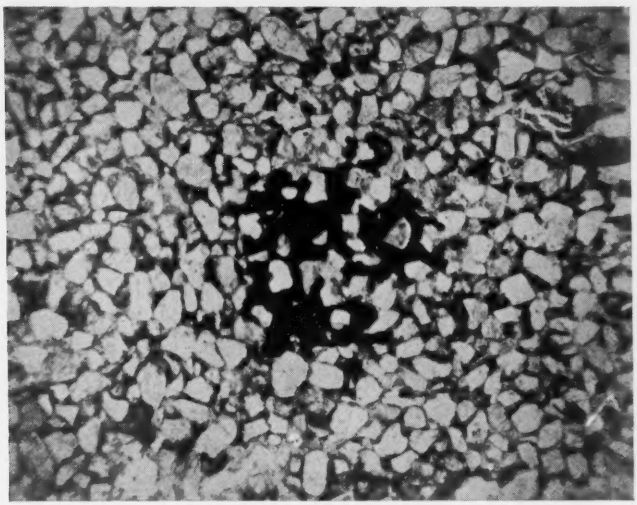

PLATE II. Spherical spot of hydrated iron oxides around a former nucleus of pyrite or marcasite. Sandstone near base of lower shale section, Spring Canyon. Polarized light. Length of line equals one millimeter.

A photomicrograph of one of these spots is shown in Plate II. It may be noted that the cementation is more spotty and irregular than is apparent in hand specimen. The ferruginate cement is distributed in and around the quartz grains as an amorphous mass.

Many joint planes in the Dakota sandstones show a concentration of iron oxide along the joints. A photograph of a typical specimen is shown in Plate III. This

PLATE III. Joint cracks filled with iron oxide. Upper Dakota sandstone near Arkins, Colorado.

is considered to be a phenomenon of case-hardening, due to the evaporation of the rock fluid at the exposed surface and the consequent precipitation of the dissolved iron content of the fluid.

DERIVATION OF CEMENTING MATERIALS

Pye (1944, p. 100) names four possible origins for secondary silicinate cement, viz.:

1. Solution of quartz and silicates
2. Deposition from sea water
3. Deposition from connate water
4. Deposition from meteoric water or circulating connate waters from other beds.

Pye concludes that, although no good evidence as to the source of the secondary silica in the Bethel sandstone existed, most of it

> . . . was derived either (1) from the sea or connate water, or (2) from the decomposition and solution of fine silica-bearing minerals.

On the other hand, Waldschmidt (1941) concludes that even if a buried sandstone were saturated with sea water, the silica present would not be sufficient to form all the quartz crystals observed in some sandstones. He believes that the source of secondary silica is the sand grains themselves. Waldschmidt's theory involves (1) compaction of sediments by the overlying strata, (2) solution of silica from sand grains at points of contact due to localized stresses, and (3) precipitation of quartz in regions of lower pressure such as on unstressed areas of sand grains and in voids. This theory is discussed in more detail in a later section.

Krynine (1941, p. 110) favors a primary origin by derivation from sea water for most of the silicinate cement of sedimentary quartzites (orthoquartzites). He states that precipitation of secondary silica

> . . . takes place at the bottom of the sea immediately following the deposition of the sand grains. This is due to a super-abundance of dissolved silica in the sea water and to conditions favorable for its precipitation.

Krynine considers secondary silicification by circulating solutions to be minor in the case of the Oriskany sand.

Van Hise (1904) postulates a belt of cementation in which most cementation occurs. It is bounded above by the belt of weathering and below by what Van Hise terms the zone of anamorphism,

> . . . the zone in which permanent openings, whether produced by fracture, original sedimentation, or any other cause, are of subcapillary size.

This belt of cementation is commonly saturated with water, which is continually circulating. Both deposition of material from the belt of weathering and solution of material from the belt of cementation takes place in the belt of cementation, with the all-pervading water acting as the means of transportation for the dissolved material. Van Hise considers that the material derived from the belt of weathering is supplemented by material contributed by igneous emanations and material which passes into solution within the belt of cementation.

In the present study, it is found that the secondary enlargement of quartz grains is more probably a simple case of growth by deposition of silica from solution on nuclei already present. This idea is substantiated by the absence of colloidal silica precipitates (chalcedony, etc.) from the sandstones which show the best secondary enlargement.

Igneous emanations and metamorphism may be of considerable local importance in the cementation of the Dakota sandstones. South of Lyons, Colorado, the Dakota section is thickened and indurated by a series of sills, particularly in the vicinity of Six-Mile Canyon. These intrusions have been studied and mapped by Hunter (1947). At other localities, faulting and folding have exerted considerable effect on cementation, both by low-grade metamorphism, and by providing fissures and channels for the percolation of subsurface water. However, there is no basis for postulating addition of material from the igneous intrusions to the Dakota sandstones.

Field and petrographic study indicates

that cementing materials in Dakota sandstones were derived by:

1. Weathering and redistribution by ground water of the ferruginous material deposited with the sediment.
2. Solution of the finer particles of quartz in the sediment.
3. Compaction of the interbedded shales of the Dakota group and the consequent expulsion of silica-bearing fluid.
4. Syngenetic deposition of argillaceous material along with the quartz grains.

Only minor amounts of silicinate cementing material seem to have been derived from the larger sand grains. Deposition of silica upon the sand grains appears to be much more important than solution. Sandstones with secondarily-enlarged quartz grains show increased angularity when compared with the normal quartz grains of sandstones of similar size-distribution.

It is suggested that the environment of deposition exerted much influence on the amount of iron oxide present in any particular stratum. Inasmuch as deposition in a paludal environment favors the formation of bog iron ore, and since the types and quantity of fossil plants found in the middle sandstone indicate that swamp conditions did prevail then, it is considered that the unusual concentration of ferruginous material in the middle sandstone is the result of its depositional environment. Undoubtedly much of this material has been redistributed by percolating ground water, but the environmental conditions controlled the amount of ferruginous material originally available in the sediment. For example, the long epoch between Morrison and Purgatoire time when the terrane was near base-level seems to have resulted in the removal by weathering of most of the iron minerals from the exposed surface. When the Washita sea advanced into the area it reworked this weathered material and deposited it as a basal transgressive sandstone which is poor in iron oxide in comparison to the other sandstones of the Dakota group. The paludal environment existing in the Front Range area about the middle of Dakota time was such as might be expected to produce local concentrations of ferruginous material. The shallow epi-continental sea was bordered by huge swampy areas of luxurious vegetation in which bog iron ores accumulated. Small fluctuations of sea level on the near base-leveled surface might shift the littoral zone landward scores of miles. When this occurred the iron would be precipitated from solution or from the colloidal state by the action of electrolytes in the sea water, and the sediment then being deposited would receive an unusually high concentration of iron. It is observed that the finer-grained layers in a given sandstone stratum contain larger amounts of ferruginous material than the coarser layers. The landward shift of the littoral zone may be partly responsible for this fact, although epigenetic factors undoubtedly altered the original distribution.

VARIATIONS IN DEGREE OF CEMENTATION

Although the porosity of a sediment affects the ease with which it may be cemented, of much more importance is the permeability of the sediment—the ease with which fluids may move through the rock. This is particularly true in secondary silicinate cementation. Where clay or iron oxide has locally filled up the voids between the quartz grains the movement of fluids through the sediment is restricted or diverted to other channels, secondary enlargement of the quartz grains is not developed, and a quartzitic texture does not occur.

Van Hise (1904, p. 618) states that

> . . . as the process of cementation advances it necessarily follows that the openings become smaller, the circulation of the water is retarded, material is transported in smaller quantity and the process becomes slower. The lessening of speed continues from the first, and when cementation is near completion it must be exceedingly slow.

Some variation in the degree of cementation may be due to this factor, but the length of time since the deposition of the Dakota group, and the dominantly quartzitic texture of the youngest (upper) sandstone member appear to minimize its importance.

The writer made a special study of variations in cementation of the Dakota group in the Boulder-Morrison area. As a general rule, the upper sandstone is most firmly cemented, the middle sandstone is intermediate in degree of lithification, and the basal sandstone (excluding the basal conglomerate) is least firmly cemented.

Two photomicrographs of the Muddy sandstone (upper sandstone of the Dakota group) are shown in Plates IV and V. The typical mosaic texture of a sedimentary quartzite is shown. No ferruginate cement is present, nor is there room for it between the secondarily-enlarged quartz grains. However, the presence of the iron oxide is shown in the hand specimen by narrow ferruginous bands (Plate VI) and is shown in thin section by conspicuous dark areas (Plate V). These dark blotches consist of tiny grains of magnetite (?), which have not been appreciably altered or hydrated. An alternate explanation is that they are being weathered, but their alteration products are dissolved and carried away by percolating ground water as fast as they form. Although the present sandstone is quite impermeable and the process is no longer operative, this solution and transportation of iron may have been of importance at one time. This may account for the unusually high iron content observed at many places in the sandy shales immediately below the upper sandstone. The downward movement of the ground water would be impeded in the relatively impervious shales and the iron dissolved from the upper sandstone added to that already widely dispersed in the shale. In addition, the increased capillary action of the finer particles of the shales would tend to absorb the fluids containing dissolved iron, the iron being precipitated in the sandy shales as one of the hydrated oxides.

From a study of the cementation of the upper sandstone of the Dakota group in the Boulder-Morrison area, the generalization is advanced that this sandstone is characterized by dominantly silicinate cement. The iron oxide in this sandstone is not hydrated and is not disseminated evenly through the sandstone, but is in the unweathered state and is localized in irregular bands and blotches throughout the rock. Following the terminology of Allen (1936), the upper sandstone would be classified as a silicinate quartz sandstone.

The middle sandstone of the Dakota group shows considerable variation in the type and degree of cementation, but it is generally less lithified than the Muddy sandstone, and more lithified than the sandstone above the basal conglomerate. The cement is in most places ferruginate, although locally silicinate, and even calcarinate at a few localities, e.g., (Turkey Creek). Some of the ferruginate cement is hematitic, most of it is limonitic, but all of it shows a definite tendency to be concentrated in the finer grain sizes. Thompson (1947) has pointed out that recent beach sands in many places show a concentration of heavy minerals in the finer-grained layers. If this factor was dominant at the time of deposition of the middle sandstone, then the concentration of ferruginous material in the finer sizes may be due to the weathering of the heavy minerals in place. An alternate explanation would be the increased effectiveness of capillary action in the finer grain sizes, resulting in the concentration of the iron-bearing solutions in the voids between the smaller particles.

The writer believes the latter explanation to be correct for the following reasons:

1. It accounts for the preferential dissemination of the ferruginous material along the smaller particles. There appears to be a direct relationship between grain size and

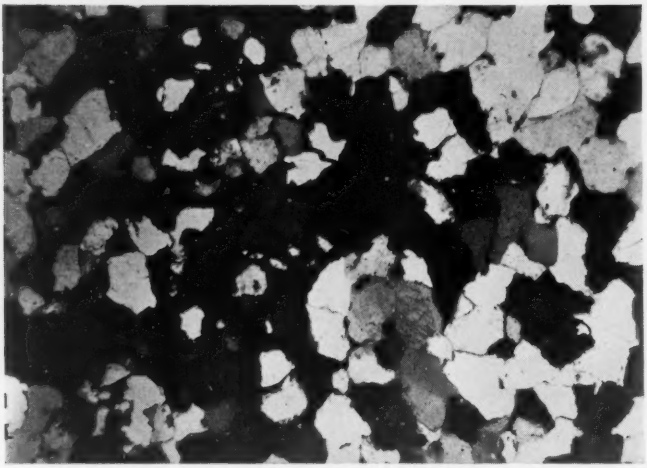

PLATE IV. Upper Dakota sandstone near Lyons, Colorado. Crossed nicols. Length of line equals one millimeter. Note the well-developed secondary enlargement of the quartz grains, producing an angularity of the detrital particles.

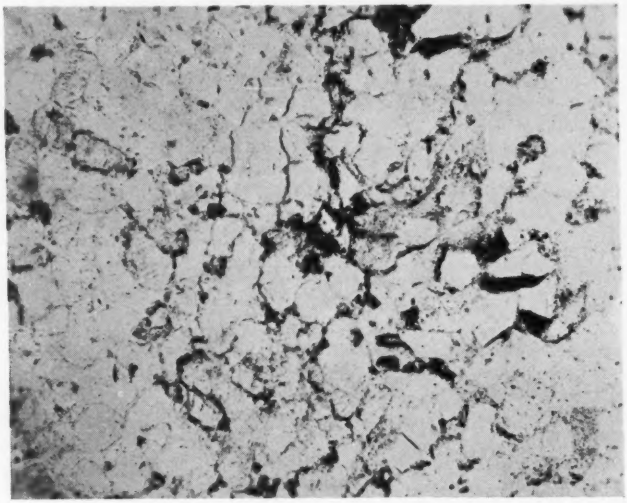

PLATE V. Upper Dakota sandstone near Lyons, Colorado. Polarized light. Length of line equals one millimeter. Well-sorted, fine-grained orthoquartzite with secondary silicinate cementation. Occasional spotty patches of unaltered magnetite grains. Quartz grains in these ferruginous areas are not as well-cemented as in the iron-free areas.

PLATE VI. Thin ferruginous laminae in upper Dakota sandstone. Lyons, Colorado.

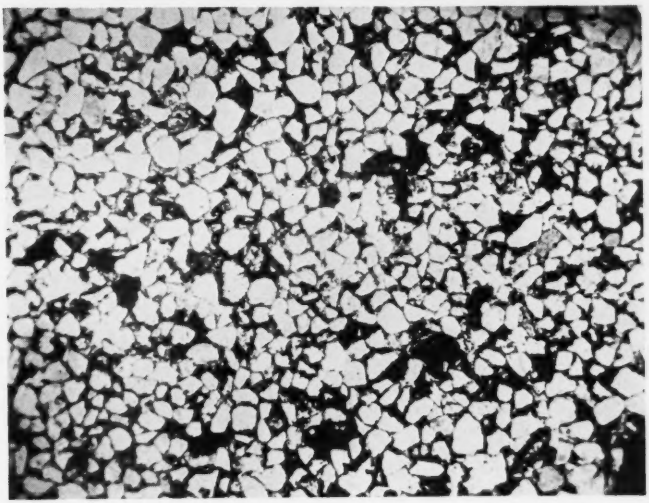

PLATE VII. Photomicrograph of slide of lower sandstone, Van Bibber Creek. Length of line equals one millimeter. Medium-grained, sub-rounded to sub-angular argillaceous quartz sandstone. Particles are not tightly packed together, secondary enlargement of quartz grains is minor.

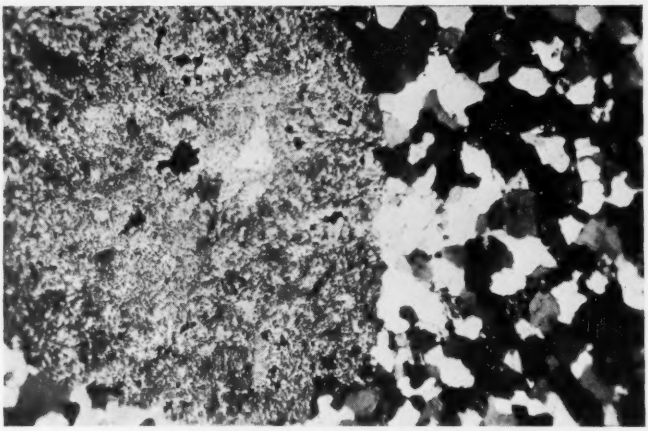

PLATE VIII

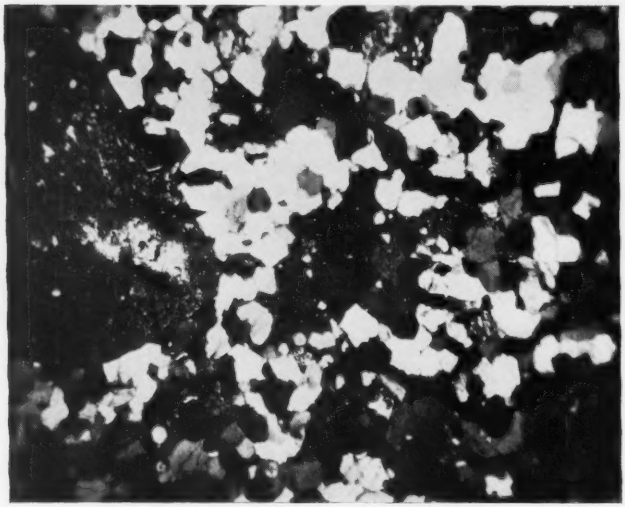

PLATE IX

PLATES VIII and IX. Photomicrographs of basal conglomerate, North side of Turkey Creek water gap south of Morrison, Colorado. Cherty granule conglomerate. Granules of chert are surrounded by quartz, chert, and quartzite grains of medium sand size. Secondary enlargement of quartz grains is very well-developed and the texture of the rock is orthoquartzitic. Length of line equals one millimeter.

amount of ferruginous material.

2. No positive evidence of the former presence of heavy minerals was found; if the ferruginous material were due to this cause one would expect to find some partially altered grains.

Plate VII shows a typical photomicrograph of the lower sandstone from Van Bibber Creek. The much greater porosity of this sandstone as compared to the sample of Muddy sandstone shown in Plates V and VI should be noticed. There are quartzitic areas, but they are minor in comparison to the areas of ferruginate and argillaceous cement. Secondary enlargement of quartz grains is poorly-developed.

Most of the outcrops of this sandstone member along the Front Range do not show the blocky angular outcrop typical of the middle and upper sandstones. Typical exposures of lower sandstone show a relatively smooth and rounded surface. This is probably due not only to the relatively poor cementation of the lower sandstone, but also to the lack of case-hardening on outcrops of this member.

The basal conglomerate, where well-developed, is well-cemented by silicinate cement in its lower portion. Ferruginate cement typically occurs in its upper part. The areas with well-developed silicinate cementation are quartzitic in texture. Two photomicrographs of the basal conglomerate are shown in Plates VIII and IX. Both photographs are made with crossed nicols. The chert pebbles consist of very fine-grained, almost cryptocrystalline silica, and are surrounded by the smaller quartz grains. The cement in these photomicrographs is silicinate and appears to have been deposited in crystallographic continuity with the quartz grains. The chert pebbles are never secondarily enlarged.

Ferruginate cement does not indurate a sand to the same degree as silicinate cement. The writer finds no example in which ferruginate cement is strong enough to cause breakage across the component grains as easily as around them. When combinations of ferruginate and silicinate cements are observed, it is found that the amount of ferruginate cement varies inversely with the degree of cementation. Argillaceous cement appears to be weaker than ferruginate cement. Argillaceous cement is more typical of the basal sandstone than of any other sandstone of the Dakota group.

Regardless of the origin of the ferruginous material—whether it is primary and deposited at the same time as the discrete particles of the sediment, or whether it was due to the weathering of iron-bearing minerals and is secondary—there is no doubt that some redistribution of this material has taken place. Circulating ground water and capillary action appear to have been the main factors in modifying the original distribution. Case-hardening of the surface outcrop is particularly noticeable in sandstones cemented by ferruginate cement, and indicates that redistribution of ferruginous material is quite important.

The lowest sandstone of the Dakota group, immediately above the basal conglomerate, is the least cemented and the least resistant of the three major sandstone members. Like the middle sandstone, silicinate, ferruginate, and calcarinate cements are found locally, but, in addition, a weak cement of clay minerals is noted in appreciable quantity in many slides. This dilution of other cements by argillaceous material renders the sandstones so friable that some specimens may be crushed between the fingers.

The basal conglomerate may be so well-cemented that it forms the crest of the Dakota hogback along the Front Range. When this occurs the Muddy sandstone forms a subsidiary hogback and the middle sandstone and shale sections are eroded down to form a saddle between the hogbacks (see Figure 1). In every outcrop where the upper sandstone forms the crest of the hogback the basal conglomerate is weak, the basal sandstone is covered by debris from the sandstone above and is difficult to delimit. (see Figure 2).

SUMMARY

Variations in cementation in the Dakota group of the Colorado Front Range are due to the following causes:

1. Type and amount of cementing material.—Silicinate cement, ferruginate cement, and argillaceous cement are the common cements in Dakota sandstones, and they are listed in order of decreasing effectiveness of lithification. Silicinate cement is the strongest, argillaceous cement the weakest. There is little calcarinate cement in Dakota sandstones, but calcarinate cement is considered to be stronger than argillaceous cement and weaker than ferruginate cement.

2. Permeability of the sediment.—Redistribution of cementing material has taken place and the sediments which were most permeable are now the most lithified. Clay minerals deposited in the voids between the quartz grains reduce permeability and prevent good cementation.

3. Degree of case-hardening.—Dakota sandstones exposed in surface outcrops are typically case-hardened. Silica and iron-bearing fluids migrate to the surface of the rock, the water evaporates, and siliceous or ferruginous material is deposited in the voids between the particles. While case-hardening exerts considerable influence on the character of the surface outcrop, it appears to be restricted to a comparatively thin surface zone.

FIG. 1. Topographic expression of Dakota group with a strong basal conglomerate. Basal conglomerate and upper sandstone form the two crests with a saddle in between.

APPLICATION OF "RIECKE PRINCIPLE" TO CEMENTATION OF SANDSTONES

Waldschmidt (1941) considers that most of the secondary silica in sandstones

of the Rocky Mountain region is due to solution of portions of the sand grains under localized stress and to the reprecipitation of the silica in regions of lower pressure and lack of stress such as in voids between the grains or upon unstressed portions of the grains. This idea appears to be an application of "Riecke's principle" to the cementation of sandstones. This law of physical chemistry had been used previously by metamorphic and structural geologists to explain the phenomenon of schistosity by recrystallization (Wright, 1906).

FIG. 2. Topographic expression of the Dakota group where the basal conglomerate is weak or is not present. Upper sandstone forms the crest.

Johnston and Niggli (1913) state "Riecke's principle" as follows:

> In other words, when a crystal is strained, the solubility on the strained face is increased. Consequently, material tends to dissolve off the strained faces of a crystal in contact with a saturated solution in any solvent, and to be redeposited where the strain is less. The effect of this is that the crystal changes in such a way as to diminish the stress upon it—an example of the well-known principle that the readjustment of a system following disturbance of equilibrium is always such as to minimize the effect of the disturbing factor.

Knopf (1933) considers that the "crystallization schistosity" explanation of change in shape of a mineral in a rock undergoing deformation cannot be based on Riecke's principle. She considers that this principle will account for the solution of stressed minerals in a rock and their deposition elsewhere but not for their deposition on other face of the stressed mineral. Knopf states that

> Although the Riecke principle will tend to equalize and reduce the grain size in a rock it

can not alter the shape of individual grains.

However, experimental work by Russell (1935) has shown that stresses can be localized in crystals and that the solubility of a part of the crystal is related to the local stress. He concludes that

> Material dissolved from one part of a crystal because of local stress may be redeposited on another part of the same crystal where the stress is relatively less, thus changing the form of the crystal. This is perhaps not a statement of the Riecke principle nor an application of it, but it seems none the less to be a valid idea.

From the work of these and other writers the present application of this principle to quartz grains may be summarized as follows:

1. Stresses may be localized in grains.
2. Material will be dissolved from the strained faces of crystals in contact with a solvent.
3. Redeposition may take place either on unstressed faces of the crystals or in voids between the crystals.

For lack of a better term the writer will continue to refer to this process as Riecke's principle because the use of the term in this manner is well-established in geologic literature.

The stress necessary for the operation of Riecke's principle occurs during compaction or induration of the sediments and is an epigenetic force, i.e., a force operative at a relatively late stage in the history of the sediment. Although Pye (1944, pp. 100–103) found ample evidence that pressure had been exerted on the grains of the Bethel sand, he concluded that proof for the solution of quartz due to pressure is meager. He based his conclusion on (1) the lack of inter-locking grain cores, (2) no evidence of solution of broken fragments, and (3) absence of mutual boundaries or stylolitic boundaries when two grains were oriented crystallographically parallel with each other.

Waldschmidt (1941) concludes that Riecke's principle is important in cementation on the basis of the following observations:

1. Interlocking of sand grains in sandstones containing appreciable recrystallized quartz.
2. Faceted quartz crystals formed around sand grains.
3. Euhedral and subhedral crystals formed independently of sand grain orientation.
4. Even distribution of recrystallized quartz, indicating a nearly uniform precipitation throughout the sandstone.
5. Number of interlocking sand grains approximately proportional to the amount of secondary quartz.

In the present study of thin sections of sandstones of the Dakota group, special attention has been paid to evidence bearing on the importance of Riecke's principle.

For the most part, the five major premises of Waldschmidt do not apply to Dakota sandstones; secondary silicinate cementation in these sandstones is not due to the action of Riecke's principle. Secondary silicinate cementation is important in some Dakota sandstones. In some slides almost every quartz grain is secondarily enlarged. In other sandstones secondary enlargement has been minor. There is every gradation in the Dakota group from friable sandstones to orthoquartzites. Well-developed crystal faces on quartz grains are found, but are not common. Pye (1944, p. 101) states that

> In quartz the pyramid ends tend to be enlarged first; if there is no room for growth of the pyramids, then the prisms are enlarged. If a grain being enlarged on a pyramid comes in contact with a grain being enlarged on a prism, the pyramid penetrates the prism enlargement and preserves its own sharp crystallographic outline.

Wayland (1939) made some detailed universal stage studies of clastic quartz grains. His conclusions are as follows:

1. That well-rounded clastic quartz grains tend to be prolate spheroids

rather than spheres, the C-axis being the direction of elongation.

2. That rhombohedral secondary enlargement is more common than that of the hexagonal prism.
3. That the prevailing elongation of the clastic quartz grains is probably due to their being longer and harder in the direction of the optic axis.

and crystallographic continuity. In the present study, this effect is observed in several slides; it is particularly clear where three grains of different orientation are secondarily enlarged towards a common center. If the microscope stage is rotated, wavy extinction under crossed nicols occurs in the more distant areas of the secondarily-deposited silica.

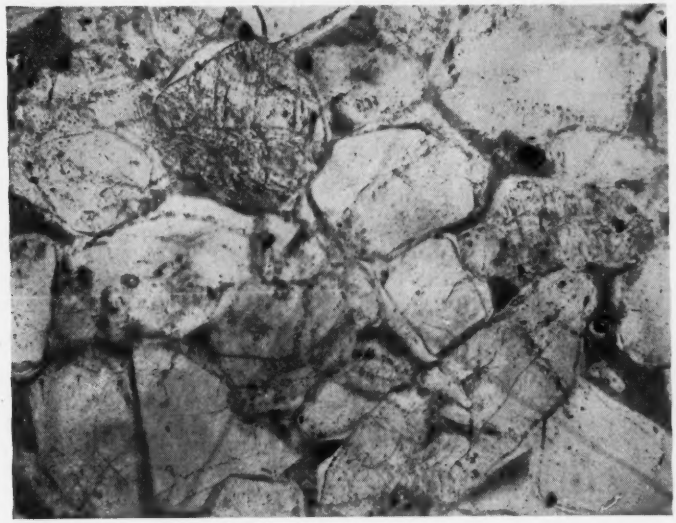

PLATE X. Photomicrograph of slide of upper sandstone, Spring Canyon. Polarized light. Length of line equals one millimeter. Well-sorted, medium-grained quartz sandstone. Secondary enlargement of quartz grains is well-developed but an orthoquartzitic texture has not been obtained.

In the present study, it is found that, irregardless of theoretical considerations, interference between adjacent grains takes place so often that secondary enlargement is largely peripheral.

The secondary enlargement of quartz grains does occur in crystallographic and optical continuity with the grain itself. Irving and Van Hise (1884), in their superb study of secondary enlargement, point out that, with increasing distance from the grain's original borders, the crystallographic force is decreased and not all the silica is deposited in optical

The ferruginous nature of many of the Dakota sandstones makes it possible to discern the original grain cores of the quartz grains. The borders of the original grains are marked out by an irregular line of inclusions of iron oxide (see Plate X). The secondary silica is clearer and has fewer inclusions.

The interlocking of sand grains in the orthoquartzites of the Dakota group is largely due to the deposition of secondary silica in voids between the grains. There are few examples of interpenetration of one grain into another, there are

no stylolitic boundaries as in metamorphic quartzites, and there is no solution of the stressed edges of broken quartz grains.

In regard to Waldschmidt's other arguments mentioned above, euhedral quartz crystals were not found although sharp angular boundaries on many grains indicate a tendency towards crystal growth. The distribution of the recrystallized quartz is spotty and uneven in the majority of the slides studied. The fact that the amount of inter-locking of sand grains is proportional to the amount of secondary quartz furnishes slight evidence for Waldschmidt's theory, for, if the grains in a sandstone are enlarged enough they will eventually meet and interlock. The degree of interlocking is a function of (1) the amount of secondary quartz, (2) the distance between the grains, and (3) the amount of foreign material (such as clay) between the grains which might hinder secondary enlargement.

Other observations concerning the importance of the Riecke principle in secondary cementation are:

1. Approximately the same amount of vertical pressure due to the load of the overlying sediments was acting upon all three major sandstone members of the Dakota group. Yet the basal sandstone is rarely quartzitic and the middle sandstone is not quartzitic in any of the samples studied by the writer. The upper sandstone member is dominantly an orthoquartzite.
2. In slides which contain a considerable amount of argillaceous or ferruginate cement, quartz grains are secondarily enlarged although the enlarged grains are separated from one another by the cement and could never have been in contact with each other or stressed by compaction of the sediment.
3. Quartzitic areas are found in parts of thin sections in which the majority of the grains show only slight secondary enlargement.
4. The smaller grains have been largely eliminated in the orthoquartzites. Certainly, unless sorting agencies were extremely effective, some small grains should have fallen into the voids between grains in such a manner that they were not in contact with other grains and subject to stress. Yet these grains are not found in the quartzitic portions of the sandstone studied. This appears to indicate that solution can be effective without stress. With decreasing grain size, a particle has proportionally more of its area exposed to chemical attack or solution. Consequently, small particles are more easily dissolved. Where quartzitic texture is not as well-developed, and where secondary enlargement is not as complete, small grains are found.

From these observations it is concluded that most solution of quartz and secondary enlargement of quartz grains is not a function of Riecke's principle. Most secondary enlargement is due to deposition of secondary silica in available voids. This silica is not derived by the solution of stressed portions of large grains, but by the solution of fine particles and, possibly to some degree, by derivation from outside sources.

I find that the only factor which consistently shows a relationship to the amount of secondary enlargement of the quartz grains and to orthoquartzitic texture is the degree of contamination of the sample, i.e., the amount of foreign material incorporated with the quartz grains at the time of deposition. It is believed that this is the dominant factor which controls secondary enlargement of quartz grains. When hydrous iron oxides or clays clog up the available voids between the grains, movement of fluids is at a minimum, secondary enlargement of quartz grains is at a minimum, and

quartzitic texture is never developed. Many ferruginous sandstones are quite hard and resistant but thin sections of them show that the quartz grains are never secondarily-enlarged to the same degree as in the white to gray sandstones of the upper Dakota sandstone and in the basal conglomerate. An excellent example of this is shown by a photomicrograph of Sample D-6 (Plate V). Note the quartzitic texture on the right and compare it with the absence of interlocking in the ferruginous band which crosses the section vertically at left center.

The basal conglomerate and the upper sandstone are, generally speaking, well-washed sands compared to other sandstone members of the Dakota group. They represent, over the Front Range area, the beaches of the Washita and Cretaceous seas (Goldstein, 1948). The upper sandstone is well-sorted; wave and current action probably winnowed it of most of the clay size particles. The basal conglomerate represents a deposit due to washing and reworking of residual silica distributed over a base-leveled surface. It may be noted that the lower sandstone above the basal conglomerate contains considerable argillaceous material, does not show quartzitic texture, and is often quite friable.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 18, NO. 3, P. 126
DECEMBER, 1948

REMARKS BY R. C. MOORE ON ENVIRONMENTAL SIGNIFICANCE OF DWARFED FAUNAS AT S.E.P.M. SYMPOSIUM DENVER, APRIL 28, 1948

The association of several dwarf faunas with oolite suggests that the conditions which give rise to oolitic limestone are conducive also to dwarfism of various invertebrates. At least, these conditions have been interpreted as representing a special environment that is reflected in the assemblage of organisms found in oolites.

Suggestion of the environmental setting represented by oolites is furnished by observations of Pennsylvanian cyclothems in Kansas and of Lower Mississippian rocks, which I have had opportunity to study, in north-central Iowa. It is characteristic of the Pennsylvanian cyclothems that the terminal marine element is an algal limestone, which in some instances consists of oolite. The fact that oolitic limestone is unknown in Pennsylvanian deposits of the northern midcontinent, except at the horizon that characteristically belongs to the algal deposits, is basis for thinking that these oolites may be algal in origin. Question arises as to the significance of the algal limestone occurrences almost exclusively at the termination of marine parts of cyclothems; they do not occur at the initial or intermediate parts of the cyclothems. Shallowness of water or nearness to shore seem not to be the sole factors involved in making the environment in which these algal deposits characteristically are formed.

In the Kinderhookian section of north-central Iowa, beds of oolitic limestone are found in the midst of a prevailing dolomite sequence of beds. The latter rocks are relatively unfossiliferous, but the oolitic limestone contains characteristic association of rhynchonellid brachiopods and the like. Inasmuch as some dolomite deposits, such as those of Permian zones in the northern midcontinent associated with red beds, are with little doubt interpreted rightly as deposits made in hypersaline waters, it is reasonable to postulate that other primary dolomites may similarly represent waters having excess saline content. If the Kinderhookian dolomite beds in Iowa are record of such conditions, one may guess that the change to oolite deposition is explainable by slight freshening of the salty sea water. Organisms that can stand the salt saturation of water in which oolite is deposited may not be able to exist in the saltier water in which the dolomite was laid down.

The suggestions just made may be applied tentatively to interpretation of the Pennsylvanian cyclothems. It seems reasonable to infer that the marginal portion of very shallow advancing Pennsylvanian seas would be fresher than normal sea water by reason of the precipitation and run-off from the adjacent land. Fossils found in the initial marine deposits of a cyclothem consist typically of phosphatic brachiopods and certain other invertebrates that seem to have been adapted to a somewhat brackish environment; among these are *Myalina*, *Derbyia*, *Juresania*, and a few other invertebrates. The marginal portions of a retreating shallow sea, on the other hand, may have had excess salinity because of evaporation in coastal lagoons and drainage of salt from connate waters in the recently exposed salt water sediments left behind the retreating sea margin. If this saltier-than-normal sea water is an environment in which algae thrive, this may be explanation for some oolites and for the restricted nature of invertebrate assemblages found in some of these deposits.

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NOTICES

NEW ROCK-COLOR CHART NOW AVAILABLE

The new Rock-color Chart is now available and can be purchased from the Division of Geology and Geography, National Research Council, Washington 25, D.C. for $5.50 per copy. This chart is designed especially for field use but is suitable also for use in the office or laboratory. It consists of 8 sheets, 5 by 7½ inches, and will fit conveniently in the back of a field notebook. It includes 115 colors which indicate the range of rock colors for all purposes. A brief text explains the system used for the chart arrangement and the color names.

The color names have been chosen to agree with the ISCC-NBS system,[1] which is already accepted by a large number of scientific organizations. The choice was designed to select a system of simple rock-color names (such as *dark reddish brown*) sufficiently standardized to be acceptable to color scientists and sufficiently useful to be satisfactory to both field and laboratory geologists.

The form and arrangement of the chart are based on the Munsell system, the most widely accepted system of color identification in the United States. In addition to the color names, the Munsell numerical designation is placed under each color for the use of those geologists who wish to make fine color distinctions by interpolating between the colors shown on the chart.

The base chart was printed by the Government Printing Office and the color chips have been hand-colored and stuck on the charts by the Munsell Color Company of Baltimore, Maryland. The colors are as permanent as it is possible to make them, and such color chips in the red, yellow, and brown ranges have been used successfully on the Soil Color Names Charts of the Department of Agriculture for nearly 10 years.

The Society of Economic Paleontologists and Mineralogists assisted in the preparation of the chart by providing many specimens of rock cuttings from wells for use in determining the range of rock colors. The chart was prepared by the Rock-Color Chart Committee representing the following organizations:

E. N. Goddard, Chairman, U. S. Geological Survey

Parker D. Trask, The Geological Society of America

Ronald K. DeFord, American Association of Petroleum Geologists

Olaf N. Rove, Society of Economic Geologists

Joseph T. Singewald, Jr. and R. M. Overbeck.

[1] National Bureau of Standards Research Paper RP 1239, now under revision.

ASSOCIATION OF AMERICAN STATE GEOLOGISTS

This committee is now a sub-committee of the Committee on Symposium on Sedimentation, Division of Geology and Geography of the National Research Council.

D. J. DOEGLAS TO ACT AS INTERNATIONAL SECRETARY FOR SEDIMENTARY PETROLOGISTS

About 40 people interested in sedimentary petrology attended a special meeting in London on Wednesday, September 1, the last day of the 18th International Geological Congress, with Percival Allen of Cambridge University presiding. The purpose of the meeting was to briefly review recent work in sedi-

mentology, particularly in Europe, and to discuss means of facilitating the exchange of ideas between those interested in this branch of geology. D. J. Doeglas discussed trends in sedimentology in the Netherlands, André Vatan outlined recent work in France, and Percival Allen summarized British work. There was considerable discussion of future trends and the relative value of various types of research.

No organization specifically devoted to sedimentology exists in Europe at present though a Congress on Sedimentary Petrology has been held in Belgium since the war and it is hoped that such congresses will continue. Jacques J. Bourcart announced that a small one is planned for May of 1949 in France; the meeting will probably be in Paris with excursions planned to the Cote de Bretagne and La Rochelle. After some discussion, the group decided not to attempt the organization of a special society or other formal organization at this time, but to appoint informally an international secretary to act as a clearing house for information. It was also decided to request the International Geological Congress to establish a Section on Sedimentology at the next meeting of the Congress.

D. J. Doeglas, Afdeling Geologie en Mineralogie, Landbouwhoogeschool, Wageningen, Netherlands, was unanimously elected International Secretary. Percival Allen, Sedgwick Museum, Cambridge University, England, was asked to prepare a summary of the discussions for distribution to those attending. It is hoped to print this summary in the next issue of the *Journal of Sedimentary Petrology.*

R. DANA RUSSELL

REVIEW

La Sédimentation continentale Tértiare dans le Bassin de Paris Meridional; André Vatan, Editions Toulousaines de L'Ingénieur, Toulouse, France, 1947, pp. 1–215, 6 plates, 30 text figures.

The author is chief of the Laboratory of the French Institute of Petroleum.

Following chapters relating to the geography and previous studies of the region under consideration, the sediments and the sedimentary conditions governing their formation are considered and the sedimentary rocks of the several formations are described in detail. This consideration forms the stratigraphic part of the memoir. The petrology of the sediments is discussed in the second part of the memoir. There is much detail. The work seems to present an excellent treatment of the Tertiary sediments of the region considered.

W. H. TWENHOFEL,
University of Wisconsin

SUGGESTIONS TO CONTRIBUTORS

TITLE

AUTHOR'S NAME
Institution
City and State

ABSTRACT

An abstract not longer than 250 words should accompany each paper. Abstracts should mention the more important new data or discoveries and the main conclusions of the paper.

INTRODUCTION

This brief style guide has been prepared by the editorial staff to aid contributors to the *Journal of Sedimentary Petrology*. It attempts to parallel the organization of a typical paper, although most papers should not, and in fact can not, be made to follow a stereotyped form. Similar guides, which use styles different from that of the *Journal of Sedimentary Petrology*, have been prepared for the U. S. Geological Survey (Wood and Lane, 1935), the Geological Society of America (Editorial Staff, 1937), and the American Association of Petroleum Geologists (Editorial Staff, 1945).

The introduction should contain a description of the area studied, the character of the problem, previous work if that can be summarized briefly and acknowledgments.

TITLE

The title should be long enough to cover the subject, but brief enough to be interesting. Subtitles are unnecessary. Few titles need be longer than 75 letters. Actually, a short descriptive title is much more apt to get a reader's attention than a long one; moreover, a short title can be repeated in its entirety in the running heads of the text pages.

HEADINGS

Primary

The word "Headings," used above, is a primary heading and is written in capital letters and centered.

Secondary

The word "Secondary," used immediately above, is a secondary heading and is written in capitals and small letters.

Tertiary.—Tertiary headings are usually unnecessary for the relatively short articles published in the *Journal of Sedimentary Petrology*. If required, however, they are written in capitals and small letters with an underscore for italics. Each begins a new paragraph, but is not an integral partof the first sentence.

WRITING

Organization

It is advisable to prepare a careful and detailed outline before writing is begun. Use of such an outline helps in organizing the paper and improves its clarity. Parts of the outline may also serve as headings.

Grammar

An effort should be made to write clearly and simply, taking special care to use short non-technical words wherever possible (Croneis, 1937). Sentences should be smooth and concise. Repeated rewriting, as well as correction following critical reading by colleagues, is usually helpful in recognizing and deleting unnecessary words. After stripping away the long technical words which overdress what may seem to be an important geological deduction, one often finds only a small and not very original idea (Smith, 1922). Wood and Lane (1935, pp. 49–102) give many examples how sentences in geological reports can be simplified and clarified. Other hints are presented by Allbutt (1923) and Trelease and Yule (1937).

Form

Manuscripts submitted for publication should be typewritten and double-spaced on standard white 8½ by 11 inch paper.

A 1½ inch margin at the left, bottom, and top, with 1 inch margin at the right of each page, leaves sufficient room for editorial comments and notes to the printer.

CITATIONS AND FOOTNOTES

Titles of published articles needed for citation should be arranged alphabetically by author and placed at the end of the paper. Proper abbreviations for the names of various journals and bulletins are given in a special pamphlet of the U. S. Geological Survey (Wood and Lane, 1935, pp. 22–29). Reference is made to the articles by author, date, and pertinent pages, as is done in this outline.

Footnotes usually are unnecessary because the information they contain can ordinarily be given more simply in the text itself. Their use should be restricted to the presentation of important facts which were discovered after the manuscript had been sent to press, and to unavoidable explanation of items in tables. Where necessary, the footnotes[1] are included in the text between parallel lines separating them from the text proper.

ILLUSTRATIONS

Preparation

One of the chief difficulties in the effective presentation of data or ideas by means of illustrations is that authors do not take the trouble to discover what happens to drawings or photographs in the process of printing. A pamphlet by Ridgway (1920) presents many helpful hints for the drafting of simple and effective illustrations. Symbols for various kinds of rocks and for map features are given in his plates 3 and 4. He also discusses the various processes of reproduction (pp. 72–90) and illustrates the effects of screening in the preparation of halftone cuts (pl. 6). One of the chief difficulties in effective presentation of drawings is that authors frequently fail to allow sufficiently for reduction. Remembering that most illustrations must be printed on regular pages, choose your line width and size of letters so they will stand out clearly after reduction. A reducing glass will help in making this estimate, though it should be remembered that the printed drawing usually is not so sharp as the original as seen through the glass.

Much additional information on illustrations is available (Moore, 1942). Moore's figures 5 and 6 show how an illustration may be clarified by omission of unnecessary detail. He also gives data on the visibility of lantern slide lettering (Moore, 1942, figs. 2, 7, 8).

Kind

All photographs and fold-ins are termed plates, because they usually are printed on paper of special quality or size. Line drawings which occupy part or all of a text page are figures.

Titles and Explanation

A short descriptive title and usually one or two short sentences of explanation are needed for each illustration. They should be typed at the appropriate place in the manuscript between lines extending completely across the page.

CONCLUSIONS

If contributors will follow these suggestions, the work of the editors will be lightened and the time between the writing of a paper and its publication may be shortened. Information on the cost of reprints will be supplied when galley proof is returned to the author.

[1] Do not use footnotes if their use can be avoided.

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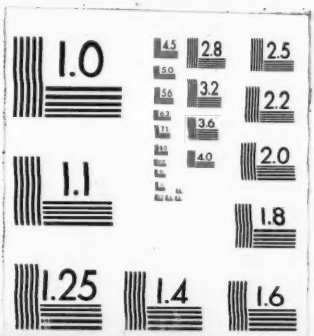
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